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A PIPE-MODEL TO ASSESS THE HYDRODYNAMIC EFFECTS OF A BLOWDOWN IN A 4-LOOP PWR

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Abstract

During the first milliseconds of a Loss Of Coolant Accident in a PWR, a depressurization wave propagates from the break through the whole primary circuit and the reactor. Then the circuit empties progressively with a diphasic regime.

The propagation delay of the depressurization wave causes local transient pressure differences between various zones of the reactor. The pressure differences around the core zone may damage the fuel assemblies and the core structures. Consequently, the reactor pressure map must be assessed during the blowdown phase.

As the depressurization process is very dependent on the break conditions, it is important to model precisely the break hydrodynamic regime and to represent the complete primary circuit.

This paper presents CASTEM-PLEXUS hydrodynamic calculations of the blowdown due to a LOCA, in the primary circuit of a four-loop-PWR. The hydraulic circuit is represented with a pipe model respecting the 3D component volumes and the average journey of the diphasic water. Specific laws complete the description for section changes and multi-pipe links.

The hydraulic peculiarities (pumps, pressure losses and the break) are taken into account thanks to additional constitutive laws and bounding conditions. The initial conditions are those of the reactor nominal rating. The calculation describes the pressure transient coupled with diphasic water mass transfers, due to the break opening and the beginning of the circuit emptying.

Keywords: LOCA, blowdown, depressurization, break, hydrodynamic loads, hydraulic circuit, PWR

1 Introduction

For the PWR safety, it is necessary to analyse the consequences of a hypothetical Loss Of Coolant Accident. From the break opening time on a primary pipe, the blowdown causes the propagation of an acoustic wave through the whole primary circuit, pipe whipping, component recoil and internal structure moving. Then the circuit empties progressively with a diphasic regime.

During the 70s, pipe whipping (Cauquelin, 1979) and split (Dupuy, 1983), pipe impact on bumpers (Caumette, 1981) and the recoil force on the vessel (Garcia, 1981) were studied with the AQUITAINE II test-facility and the TEDEL, TRICO and TITUS (Garcia, 1982) codes.

The acoustic response was assessed by a monodimensionnal modal analysis (Gibert, 1988) (Lepareux[a], 1974) with the monophasic fluid represented with an added mass. The transfert function of the circuit was computed with the VIBRAPHONE code (Lepareux, 1975) and the circuit response with the TRANSIT code. Both codes had been qualified (Lepareux[b], 1974) on the WHAM blowdown test-facility (Gruen, 1970).

During the 80s, by using an improved modal approach (Jeanpierre, 1979) (Guilbaud, 1983) taking into account the fluid-structure interaction, the effects of the LOCA acoustic phase on the reactor internal structures (Guilbaud, 1985) (Guilbaud, 1987) were calculated with a set of three codes: TEDEL for the pipes, AQUAMODE for the axisymmetrical vessel with the internal structures and fluid, and TRISTANA for the connections.

Now, a single code dedicated to Fast Dynamic Analysis is sufficient to carry out hydrodynamic calculations involving acoustic transients and fluid mass transfers. CASTEM-PLEXUS is a general fast dynamic analysis computer code developped by the CEA-DMT (Chavant, 1979) (Hoffmann, 1984). Its main applications are impacts, explosions, pipe transients and hydrodynamics (Robbe[b], 1999).

CASTEM-PLEXUS uses the finite element method and an explicit time resolution. It is devoted to the mechanical analysis of accidental situations in one, two or three dimensions, involving structures and fluids with or without coupling. Its formulation can be either Lagrangian, Eulerian or A.L.E. (Arbitrary Lagrange Euler) according to the problem dealt with. Possible material or geometric non-linearities are taken into account.

After the validation of the CASTEM-PLEXUS code for pipe circuits (Lepareux[a], 1985) (Millard, 1985) (Lepareux[b], 1985) on test-facilities (Couilleaux, 1984), first calculations were performed on a HDR reactor (Schwab, 1989) (Lepareux, 1991) (HDR Sicherheltsprogramm, 1980) with water initially at rest and described by a simplified diphasic constitutive law.

The models were improved to enable computations with a water law based on the steam tables of (Haar, 1984) and including several updating of all the thermodynamic variables in a time step in order to fit better with the fast evolution of the water data. Besides, the coolant initial conditions are now close to the PWR operating conditions. Previous

CASTEM-PLEXUS computations were carried out to assess the LOCA hydrodynamic effects in the primary circuit of a three-loop-PWR (Robbe^a, 1999) (Robbe, 2000).

As the blowdown process much depends on the break conditions, the hydraulic model of the break was improved in order to better take into account the water diphasic regime at the break.

This paper presents CASTEM-PLEXUS hydrodynamic calculations of the first milliseconds following the guillotine break opening, in case of a LOCA, in the complete primary circuit of a four-loop-PWR. The geometrical and hydraulic models, the initial conditions and the calculation are successively described. The results concern the propagation of the depressurization acoustic wave, coupled with the transient fluid flow, along the circuit and their effects on the reactor internal structures.

2 Geometrical model

The main primary circuit of a four-loop PWR is composed of a reactor and four primary loops, symmetrically located (fig. 2). Each loop contains a steam generator, a pump and three pipes: a hot leg, a U leg and a cold leg (fig. 1). The pressurizer and the expansion line are not studied here because their influence is not essential during the first milliseconds of a blowdown and because their representation introduces numerical instability. The thermal transfers with the pressurizer are not represented and the calculations are supposed adiabatic.

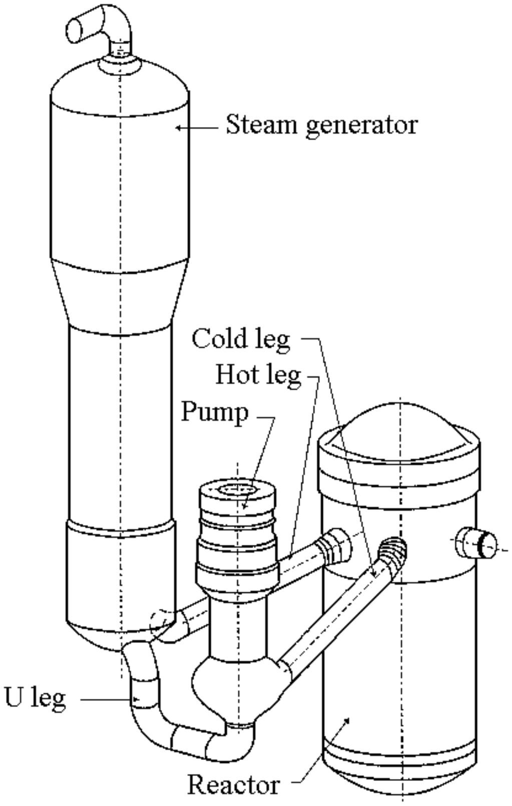


Figure 1: A primary circuit loop

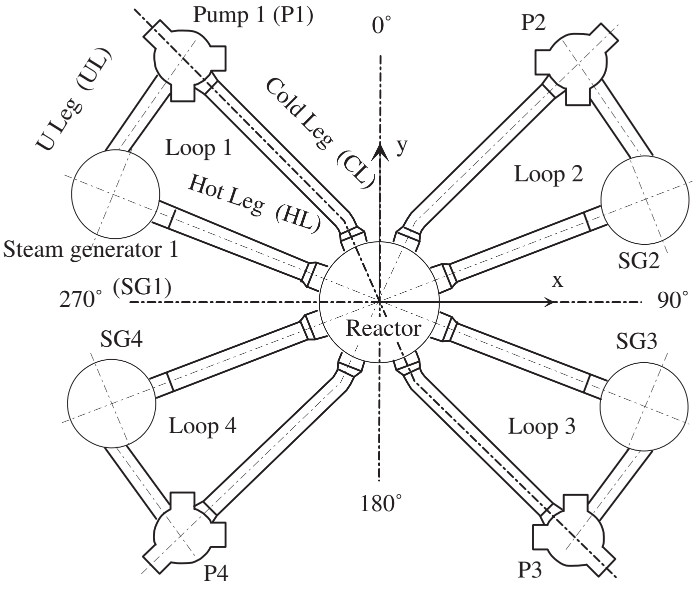


Figure 2: The primary circuit (top view)

We assume that the structures are fixed and infinitely rigid during the blowdown and that the fluid flow is monodirectional. Thus, the hydraulic circuit is represented with a pipe model respecting the 3D component capacities and the average distances covered by the water. Specific laws complete the description for geometrical peculiarities (section changes and multi-pipe links).

The four loops are schematized the same way. The internal fluid of the legs is easily represented with pipes. For the steams generators (fig. 3), the pipe bundle is considered as a unique pipe whose cross-section and lenght are respectively equal to the total pipe set cross-section and the average bundle length. The water chambers are simulated with thick short pipes going from the nozzle to the intersection point of the bundle barycentre and the flow distribution baffle.

The pump (fig. 4) is described by a vertical pipe for the water guide, an upside-down V pipe for the diffuser and the casing and by a short horizontal pipe for the discharge nozzle. The volume of the pipe-model corresponds to the primary water volume running inside the pump, neglecting the upward flow towards the controlled-leakage shaft seals. The pipe length corresponds to the shortest water path between the pump entrance and the exit, supposing a vortex absence in the casing.

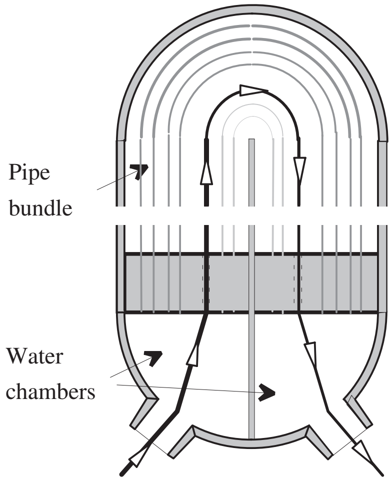


Figure 3: The steam generator

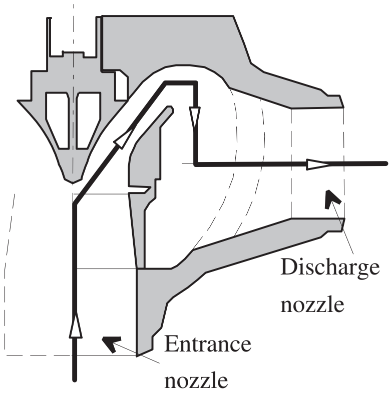


Figure 4: The hydraulic part of the pump (section)

The reactor is split up into six fluid zones (fig. 5). We represented only the space taken by water, substracting the internal structure volume to the global reactor one.

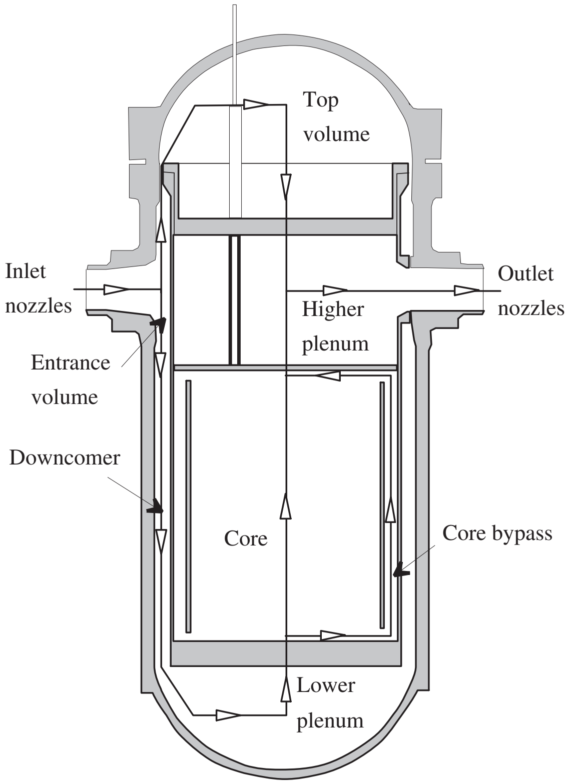


Figure 5: The reactor

- The downcomer is contained between the reactor vessel and the core barrel.
- The lower plenum comes from the reactor bottom to the top of the core support plate.
- The core cross-section is the free space around the fuel assemblies, the instrumentation tubes and the RCC guide tubes.
- The core bypass is the area between the core barrel and the baffle assembly.
- The higher plenum includes the upper core plate and goes until the bottom of the guide tube support plate.
- The top volume is composed of the volume below the closure head and the water volume inside RCC guide tube support plate.

The pipe length is calculated using the average water route inside each zone: halfway between the vertical downcomer walls, midway down the lower plenum, in the middle of the core and the higher plenum and then going out directly by the outlet nozzle.

The flow restrictions due to grids or perforated plates are not modelled geometrically but their hydraulic effects are taken into account thanks to pressure losses. The mesh of the complete circuit is presented on figure 6.

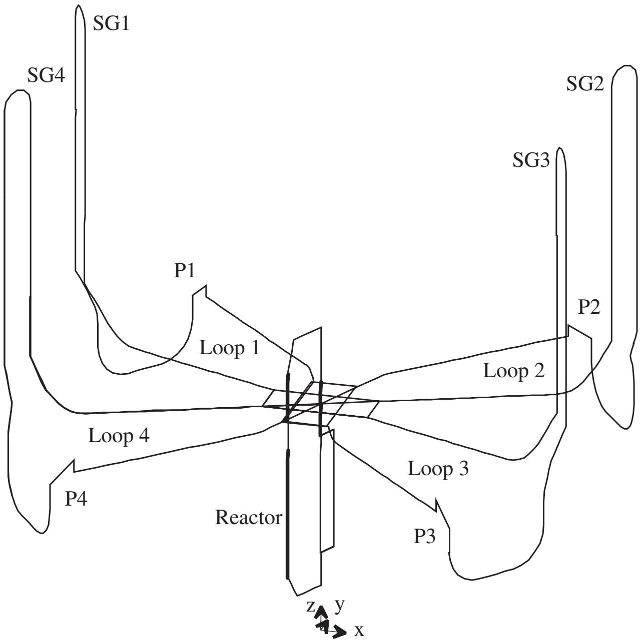


Figure 6: Pipe model of the PWR

3 Hydraulic model

The PWR coolant fluid is described by a classical diphasic water constitutive law (Papon, 1990). During the vaporization phase, liquid water and steam are supposed to be at equilibrium (same pressure, same temperature, same velocity), except at the break. From the mixture density and enthalpy within an element, the pressure, temperature, void fraction and other thermodynamic parameters are given by steam tables (Haar, 1984).

The hydraulic peculiarities are the pumps, the pressure losses and the break. The pump characteristic gives the pressure increment. In normal operation, the fluid is accelerated. But in accidental operation, the pump is considered out of order if the flow is out of the characteristic range.

Distributed pressure losses (Idel'Cik, 1986) are applied to the legs, the tube bundles of the steam generators (SG), the downcomer and the core. The distributed pressure losses come from friction (along pipe linings, vessel walls or fuel assemblies), flow direction changes in the elbows (for the legs and the top of the SG bundle) and section changes in the diverging cones at the SG inlets. The pressure loss coefficients for normal operation are kept for the LOCA calculations.

Local pressure drops (Idel'Cik, 1986) are applied:

- at the level of the SG flow distribution baffles and for the cross section changes in the water chamber nozzles,
- at the reactor inlets and outlets owing to the 1D-3D flow changes between the pipes and the reactor,
- at the top of the lower plenum because of the core support plate,
- at the bottom of the higher plenum because of the upper core plate.

For the core bypass and the top volume, as the cross section restrictions at inlet and outlet are not geometrically represented, the flow rate is imposed thanks to a pressure drop equal to the one of the parallel circuit:

- for the core bypass: Δp of the core, shared out between the inlet and outlet of the core bypass,
- for the top volume: Δp of the main circuit, distributed along the top volume pipe because it is a very high value.

A guillotine rupture is applied to the U leg of the first loop, just downstream the steam generator. The break conditions govern the dynamic mass transfers of the pressurized internal fluid. The initial liquid water vaporizes almost instantaneously and its speed is limited by the diphasic critical flow rate.

The CASTEM-PLEXUS available break models suppose a monodimensionnal annular flow, steady-state operating conditions, a pressure and thermal equilibrium between both phases, an isentropic flow and the total energy conservation according to Moody and Fauske hypothesises. Among these models, we used a Moody model (Moody, 1965), including a phase slide (liquid water and steam have different velocities).

In the CASTEM-PLEXUS code, the mesh is realised with TUBE elements for pipes, BIFURCATION elements to join two or more pipes with a different diameter and CL1D elements for local boundary conditions (local pressure drops, pumps, break). WATER and

FRICTION constitutive laws are used for the coolant fluid and the distributed pressure losses. Specific IMPEDANCE constitutive laws describe the boundary conditions.

4 Initial conditions

The calculations are initialized at the reactor nominal rating. The initial pressure is 15.5 MPa. The temperature of the circuit is supposed constant and equal to 311°C. Thus, according to (Haar, 1984), the water density is 702 kg/m^3 and the sound velocity is 950 m/s.

The flow distribution in the reactor is given for a "hot dome" configuration: only 0.4 % of the reactor inlet flow goes through the top volume. We consider that this configuration gives more pessimistic hydrodynamic loads in the core than the "cold dome" configuration, where 3.5 % of the total flow is diverted through the top volume.

The full flow is 6.81 m^3/s per loop, what means 27.23 m^3/s at the reactor inlet and outlet. According to the top volume flow hypothesis, the main flow (in the downcomer, the lower plenum and the higher plenum) reaches 99.6 % of the reactor inlet flow. The core flow is equal to 96.5 % of the main flow, what means that the remaining 3.5 % are going through the core bypass.

A conventional double ended break is represented. The outside pressure is 1 bar and the tear lasts 1 ms.

5 Results

The calculation was carried out in normal operation until 1000 ms of physical time. Then the break opens in 1 ms and the LOCA computation is performed for 1000 ms more of physical time.

Figures 10a to 10w show the volumic flow in the complete circuit from the rupture time and allow to understand the chronology of the blowdown wave propagation. Figure 11 presents the water mass lost by the break. Figures 12a to 12c and figures 13a to 13c describe respectively the pressure and the density in the circuit at nominal rating and after the rupture.

The stabilization of the nominal rating computations close to the initial conditions prove the coherence of the global hydraulic model.

The break opening causes an almost instantaneous pressure drop at the break until the critical pressure. The liquid water vaporizes and the flow increases until the diphasis critical flow rate (about 220 m^3/s from 300 ms after the rupture time). The water mass lost at the break reaches 30 tons after 1 s.

In the broken loop, the flow increases on the hot side. In the zone next to the break, it follows the progressive rise imposed by the break. Farther, the flow increases from 7 m^3/s to 20 m^3/s around 80 ms after the rupture and then progressively decreases. On the cold side, the water speed slows down, becomes zero before the discharge changes direction. The model considers the pump stopped.

For the pressure and the density, a gradient sets up between the break and the reactor nozzles. At the end of the calculation, the water near the reactor nozzles only starts to become diphasic whereas it is immediately diphasic at the break. On the same way, the pressure varies from 3.5 MPa at the break to 9.5 MPa next to the reactor.

The three non-broken loops behave the same because the model does not allow 3D dissymmetry. The discharge continues in the same direction. The water speed descreases on the hot side of the loop whereas it increases on the cold side. The change between both behaviours occurs more or less half-way the loop. At the reactor outlet, the water is attracted by the broken loop rather than the hot legs of the non-broken loops because of the higher pressure gap with the break. On the contrary, the pumps push more in the cold legs to feed the broken loop cold leg whose flow is oriented outwards.

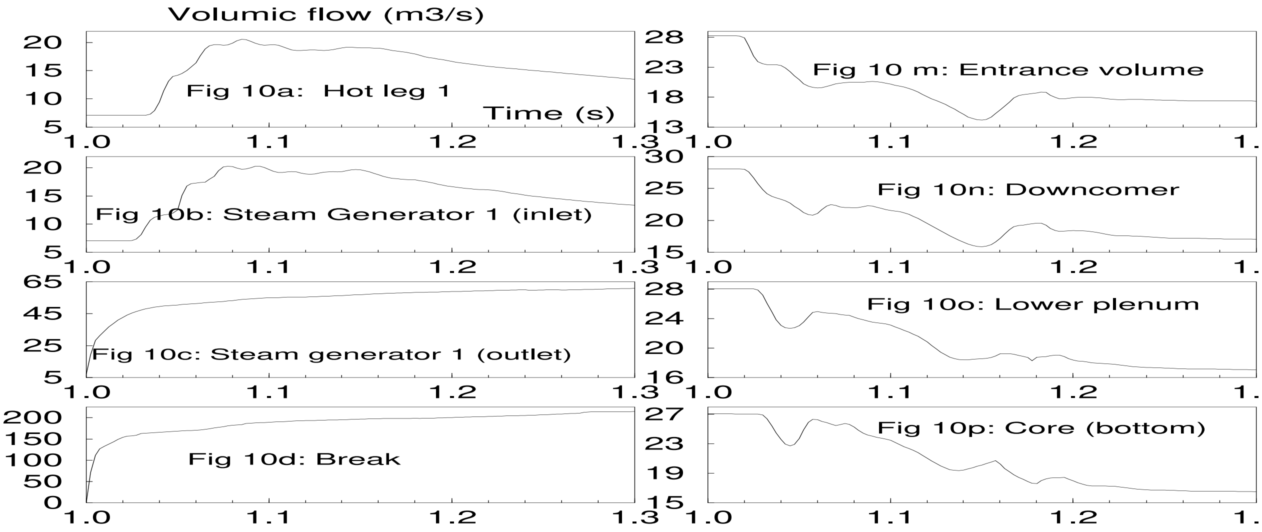
From 150 ms after the rupture, the pressure falls around 9.5 MPa in the whole non-broken loops. The density decreases much more in the U legs than near the reactor: the reactor feeds the hot legs but less than at nominal rating, the pumps empty the middle of the loops to feed the loop 1 cold leg and the reactor entrance volume.

As in the non-broken loops, the reactor is divided into two zones for the flow variations. The flow decreases in the reactor volumes near the reactor inlets (entrance volume, downcomer, lower plenum, bottom of the core and the core bypass, inlet of the top volume). Because of the 1D representation of the circuit, the four loops and the reactor entrance volume inlet are directly connected. Thus the non-broken loops directly feed the broken loop rather than the reactor. In the rest of the reactor, the flow starts increasing: the reactor empties to feed the broken loop hot leg. The flow decreases later.

Globally, the pressure is more or less the same in the whole reactor (9.5 MPa after 150 ms). A finer analysis would show pressure gaps between the different reactor zones. The density goes down in the whole reactor but less than in the loops. The density decreases more in the volumes close to loop connection than in the reactor centre.

Figures 10: Volumic flow

Figure 11: Water mass lost by the break



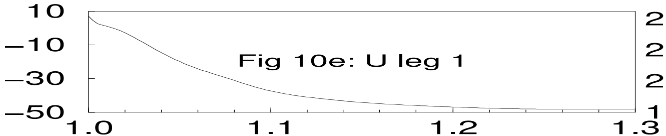


Fig 10e: U leg 1

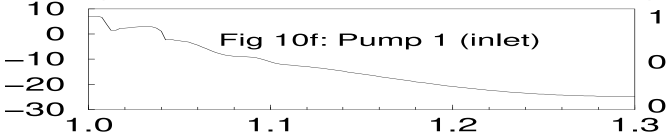


Fig 10f: Pump 1 (inlet)

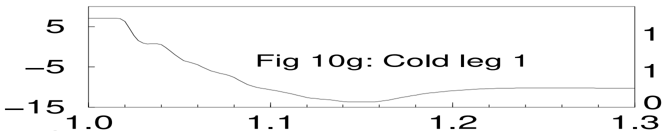


Fig 10g: Cold leg 1

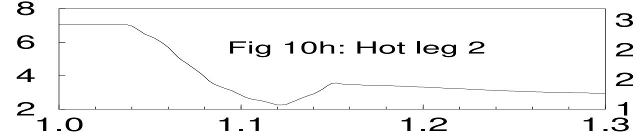


Fig 10h: Hot leg 2

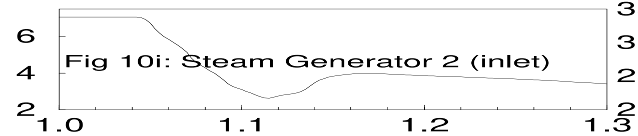


Fig 10i: Steam Generator 2 (inlet)

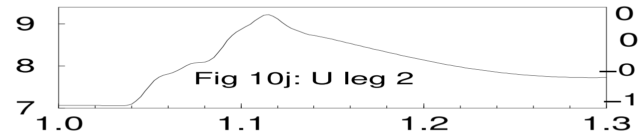


Fig 10j: U leg 2

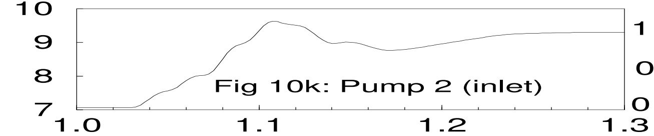


Fig 10k: Pump 2 (inlet)

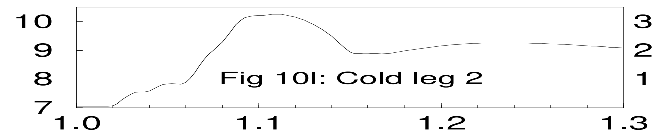


Fig 10l: Cold leg 2

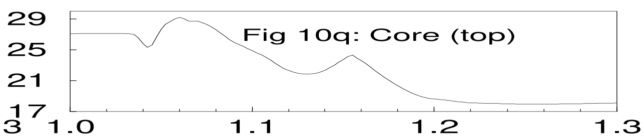


Fig 10q: Core (top)

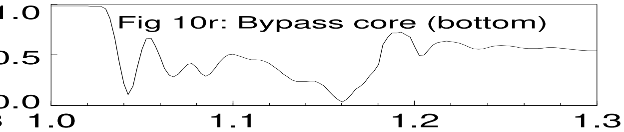


Fig 10r: Bypass core (bottom)

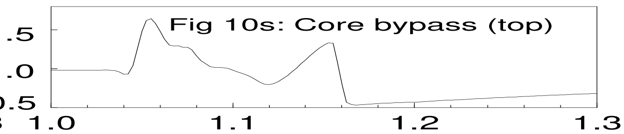


Fig 10s: Core bypass (top)

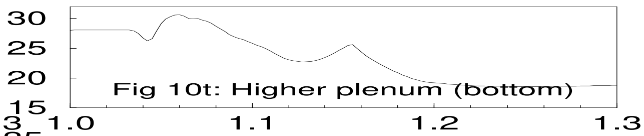


Fig 10t: Higher plenum (bottom)

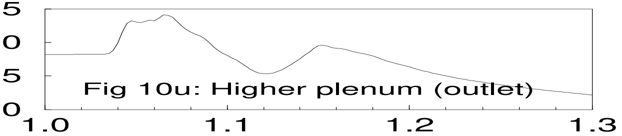


Fig 10u: Higher plenum (outlet)

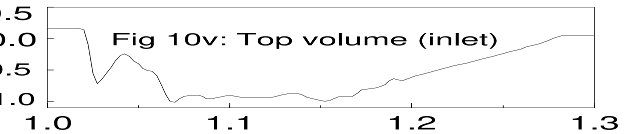


Fig 10v: Top volume (inlet)

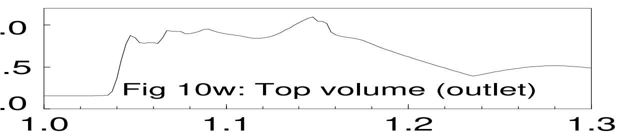


Fig 10w: Top volume (outlet)

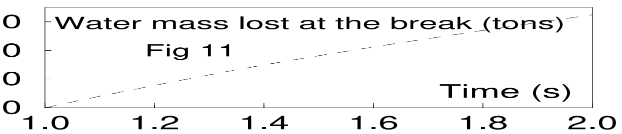
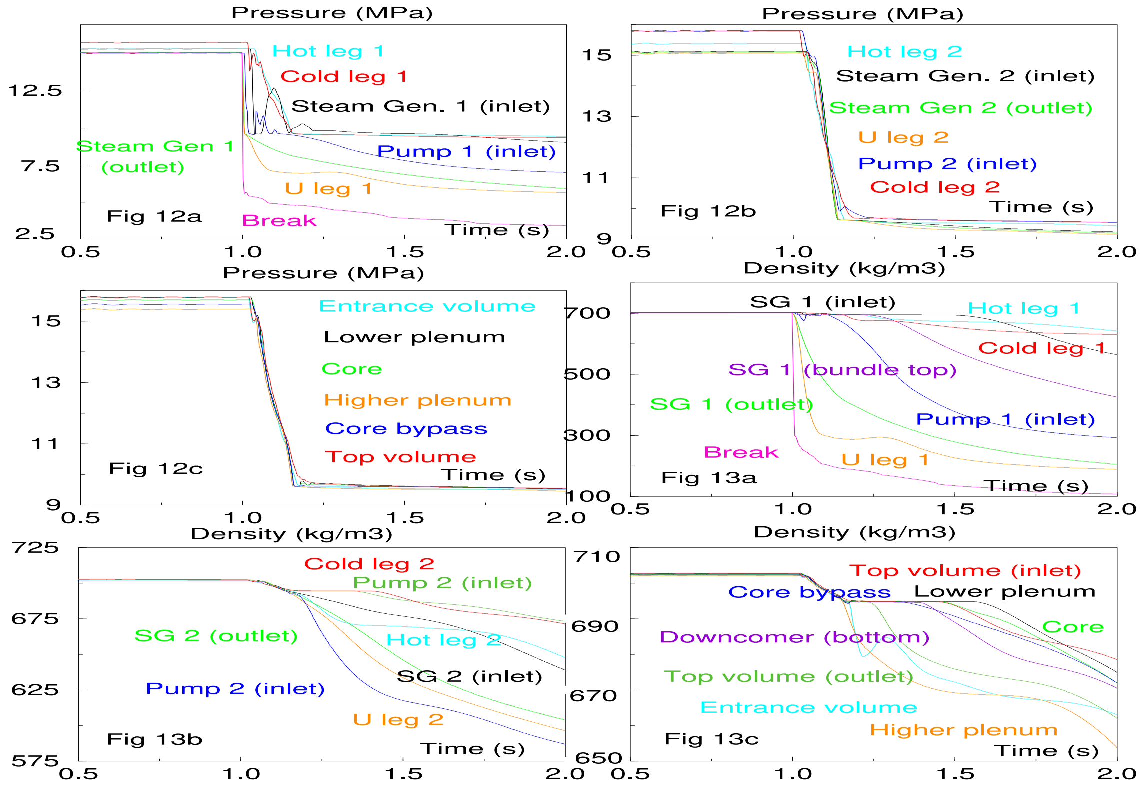

Water mass lost at the break (tons)

Fig 11

Figures 12: Pressure Figures 13: Density



6 Conclusion

The hydrodynamic loads due to a LOCA were computed successfully with the CASTEM-PLEXUS code, by means of an hydraulic pipe-model of the complete primary circuit and the reactor. This paper mainly presents the geometrical and hydraulic model. The computation results will be detailled in (Potapov, 2000).

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